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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

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INVENTOR(S)

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☒ *Additional inventors are being named on the _____ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

Generalized, 3D Surface Multiple Prediction (3D GSMP)

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ENCLOSED APPLICATION PARTS ***(check all that apply)***

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☐ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☐ Applicant claims small entity status. See 37 CFR 1.27.

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

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Respectfully submitted,
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William H.	Dragoset	Houston, Texas

Number 2 of 2

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UNITED STATES PATENT APPLICATION FOR:

GENERALIZED 3-D SURFACE MULTIPLE PREDICTION

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ATTORNEY DOCKET NUMBER: 594-25608 WGEC/0030L

CERTIFICATION OF MAILING UNDER 37 C.F.R. 1.10

I hereby certify that this New Application and the documents referred to as enclosed therein are being deposited with the United States Postal Service on April 7, 2004, in an envelope marked as "Express Mail United States Postal Service", Mailing Label No. EV416702118US, addressed to: Mail Stop PATENT APPLICATION, Commissioner for Patents, P.O. Box 1450, Alexandria, VA. 22313-1450.

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GENERALIZED 3-D SURFACE MULTIPLE PREDICTION

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] Embodiments of the present invention generally relate to marine seismic surveying and, more particularly, to a method for attenuating the effect of surface multiples in a marine seismic signal.

Description of the Related Art

[0002] Seismic surveying is a method for determining the structure of subterranean formations in the earth. Seismic surveying typically utilizes seismic energy sources which generate seismic waves and seismic receivers which detect seismic waves. The seismic waves propagate into the formations in the earth, where a portion of the waves reflects from interfaces between subterranean formations. The amplitude and polarity of the reflected waves are determined by the differences in acoustic impedance between the rock layers comprising the subterranean formations. The acoustic impedance of a rock layer is the product of the acoustic propagation velocity within the layer and the density of the layer. The seismic receivers detect the reflected seismic waves and convert the reflected waves into representative electrical signals. The signals are typically transmitted by electrical, optical, radio or other means to devices which record the signals. Through analysis of the recorded signals (or traces), the shape, position and composition of the subterranean formations can be determined.

[0003] Marine seismic surveying is a method for determining the structure of subterranean formations underlying bodies of water. Marine seismic surveying typically utilizes seismic energy sources and seismic receivers located in the water which are either towed behind a vessel or positioned on the water bottom from a vessel. The energy source is typically an explosive device or compressed air system which generates seismic energy, which then propagates as seismic waves through the body of water and into the earth formations below the bottom of the water. As the seismic waves strike interfaces between subterranean formations, a

portion of the seismic waves reflects back through the earth and water to the seismic receivers, to be detected, transmitted, and recorded. The seismic receivers typically used in marine seismic surveying are pressure sensors, such as hydrophones. Additionally, though, motion sensors, such as geophones or accelerometers may be used. Both the sources and receivers may be strategically repositioned to cover the survey area.

[0004] Seismic waves, however, reflect from interfaces other than just those between subterranean formations, as would be desired. Seismic waves also reflect from the water bottom and the water surface, and the resulting reflected waves themselves continue to reflect. Waves which reflect multiple times are called "multiples". Waves which reflect multiple times in the water layer between the water surface above and the water bottom below are called "water-bottom multiples". Water-bottom multiples have long been recognized as a problem in marine seismic processing and interpretation, so multiple attenuation methods based on the wave equation have been developed to handle water-bottom multiples. However, a larger set of multiples containing water-bottom multiples as a subset can be defined. The larger set includes multiples with upward reflections from interfaces between subterranean formations in addition to upward reflections from the water bottom. The multiples in the larger set have in common their downward reflections at the water surface and thus are called "surface multiples". Figure 1, discussed below, provides examples of different types of reflections.

[0005] Figure 1 shows a diagrammatic view of marine seismic surveying. The procedure is designated generally as 100. Subterranean formations to be explored, such as 102 and 104, lie below a body of water 106. Seismic energy sources 108 and seismic receivers 110 are positioned in the body of water 106, typically by one or more seismic vessels (not shown). A seismic source 108, such as an air gun, creates seismic waves in the body of water 106 and a portion of the seismic waves travels downward through the water toward the subterranean formations 102 and 104 beneath the body of water 106. When the seismic waves reach a seismic reflector, a portion of the seismic waves reflects upward and a portion of the seismic

waves continues downward. The seismic reflector can be the water bottom 112 or one of the interfaces between subterranean formation, such as interface 114 between formations 102 and 104. When the reflected waves traveling upward reach the water/air interface at the water surface 116, a majority portion of the waves reflects downward again. Continuing in this fashion, seismic waves can reflect multiple times between upward reflectors, such as the water bottom 112 or formation interfaces below, and the downward reflector at the water surface 116 above, as described more fully below. Each time the reflected waves propagate past the position of a seismic receiver 110, the receiver 110 senses the reflected waves and generates representative signals.

[0006] Primary reflections are those seismic waves which have reflected only once, from the water bottom 112 or an interface between subterranean formations, before being detected by a seismic receiver 110. An example of a primary reflection is shown in FIG. 1 by raypaths 120 and 122. Primary reflections contain the desired information about the subterranean formations which is the goal of marine seismic surveying. Surface multiples are those waves which have reflected multiple times between the water surface 116 and any upward reflectors, such as the water bottom 112 or formation interfaces, before being sensed by a receiver 110. An example of a surface multiple which is specifically a water bottom multiple is shown by raypaths 130, 132, 134 and 136. The point on the water surface 116 at which the wave is reflected downward for the second time is generally referred to as the downward reflection point. The surface multiple starting at raypath 130 is a multiple of order one, since the multiple contains one reflection from the water surface 116. Two examples of general surface multiples with upward reflections from both the water bottom 112 and formation interfaces are shown by raypaths 140, 142, 144, 146, 148 and 150 and by raypaths 160, 162, 164, 166, 168 and 170. Both of these latter two examples of surface multiples are multiples of order two, since the multiples contain two reflections from the water surface 116. In general, a surface multiple is of order i if the multiple contains i reflections from the water surface 116. Surface multiples are extraneous noise which obscures the desired primary reflection signal.

[0007] Surface multiple attenuation is a prestack inversion of a recorded wavefield which removes all orders of all surface multiples present within the marine seismic signal. Unlike some wave-equation-based multiple-attenuation algorithms, surface multiple attenuation does not require any modeling of or assumptions regarding the positions, shapes and reflection coefficients of the multiple-causing reflectors. Instead, surface multiple attenuation relies on the internal physical consistency between primary and multiple events that must exist in any properly recorded marine data set. The information needed for the surface multiple attenuation process is already contained within the seismic data.

[0008] Various prior art methods have been tried for removal of surface multiples from recorded traces. It has been noted, for example, that the travel time for a surface multiple, the path of which is entirely in the water during an oceanographic expedition, is a function of the "offset", the distance between the source and receiver, and the number of times the multiple reflects from the surface. For example, if the multiple reflects from the surface once before being received by the microphone and the offset is zero, the multiple's travel time is exactly twice that of the principal waves. This fact has been used in various schemes to remove multiples.

[0009] Other methods involve complex ray tracing schemes which generate a synthetic multiple wave and subtract it from the actual wave to obtain a supposedly multiple free record. However, these methods are very awkward in that they require significant knowledge of the subsea structure as well as the ocean bottom configuration before the synthetic wave can be generated. Similar synthetic multiples can be generated using more accurate methods not directly involving ray tracing, e.g., field propagation techniques, but again these require detailed knowledge of at least the ocean bottom, as well as the shape of the subsea interfaces, and so are not as practical as would be desired.

[0010] Therefore, a need exists in the art for an improved method for removing the record of multiple surface reflection events from seismic records for data processing purposes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The following detailed description makes reference to the accompanying drawings, which are now briefly described.

[0012] Figure 1 illustrates a diagrammatic view of marine seismic surveying.

[0013] Figure 2 illustrates a plan view of the geometry.

[0014] Figure 3 illustrates step 1 described herein in accordance with one embodiment of the invention.

[0015] Figure 4 illustrates steps 2 and 3 described herein in accordance with another embodiment of the invention.

[0016] Figure 5 illustrates a computer network into which embodiments of the invention may be implemented.

DESCRIPTION OF THE INVENTION

[0017] The following works listed below may provide additional background, definitions and support for the present invention:

- US Patent Application Serial No. 10/668,927 issued to Moore entitled "Method for the 3D Prediction of Free Surface Multiples."
- Levin, S. A., 2002, Prestack poststack 3D multiple prediction: 72nd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, SP3-05.
- Sun, Y., 1999, Anti-aliasing multiple prediction beyond two dimensions: Stanford Exploration Project, Report 100, 159-171.

3D GSMP (generalized surface-related multiple prediction)

[0018] 3D GSMP is a generalized implementation of the 3D surface-related multiple prediction (SMP) algorithm, in the sense that it makes no assumptions about the regularity or distribution of traces in the recorded dataset. As such, there is no concept of a nominal geometry, and the recorded dataset is simply treated as a collection of traces defined by their source and receiver locations. The 3D GSMP algorithm will predict multiples for any set of traces similarly defined by their source and receiver locations.

[0019] The algorithm is designed to take account of all the irregularities in the acquisition geometry, and this is particularly important in the presence of cable feathering. Note however that the accuracy of the predicted multiples is dependent on the distribution of traces in the recorded dataset. The algorithm is designed to be optimal for a given trace distribution, and adapts according to that distribution, but a poorly sampled dataset will not provide a good prediction. For a perfectly regular dataset, the algorithm essentially reduces to the 3D SMP algorithm.

[0020] The proposed method, known as 3D Generalized Surface Multiple Prediction (3D GSMP) predicts surface multiples in a manner similar to 3D SMP, but makes no assumptions about the regularity of the input data. In particular, multiples are predicted at the correct location, offset and azimuth. The computational cost is similar to that of 3D SMP. The algorithm is derived so as to be efficient given the organization of the recorded dataset.

[0021] In the following, 3D SRME refers to a general implementation of SRME yielding a 3D prediction, 3D SMP refers more specifically to the method of that name used within WesternGeco (Moore, 2003) and 3D GSMP refers to the new method described here.

[0022] In general, surface multiple prediction algorithms require convolutions of pairs of traces, for which the receiver location for one trace of the pair is coincident with the shot location for the other trace. Since source and receiver locations in

recorded data are never precisely coincident, it is normal to regularize the datasets to a nominal geometry such that this coincidence of source and receiver locations is achieved. The multiples are then predicted for this regular geometry, and then deregularized to the original geometry before subtraction.

[0023] Unfortunately, the regularization and (especially) the deregularization processes are never perfectly accurate, and can lead to significant errors in the predicted multiples. The GSMP process aims to minimize these errors by minimizing the work done by the regularization process, and avoiding the deregularization process completely.

[0024] 3D SMP is efficient because most of the processing work is done on a subsurface line (SSL) basis, i.e. the data on each SSL is processed independently of other SSLs. In particular, each convolution involves pairs of traces from the same SSL. Only after all the convolutions are computed, are data from different SSLs combined. In order to minimize regularization requirements, 3D GSMP works with data from many SSLs at once, and in general the convolutions will involve traces from different SSLs. In order to maintain the efficiency associated with SSL-based processing, the algorithm is formulated so as to work on pairs of SSLs at once.

Assumptions

[0025] Figure 2 shows a plan view of the geometry. In the following, upper-case letters are used to denote locations of specific points, as shown in the figure, and the corresponding lower-case, bold-font letter is used to denote the vector location of that point relative to the origin.

[0026] The algorithm makes the following assumptions about the recorded data.

1. The input dataset is a collection of prestack traces defined by midpoint ($\mathbf{m}$), offset (x) and azimuth (θ). Azimuth may be defined relative to any fixed direction, and may or may not allow for reciprocal traces to be considered equivalent (i.e. for traces whose azimuths differ by 180° to be considered equivalent). Although

no regularity is assumed, the dataset must provide reasonable coverage in midpoint-offset (and ideally azimuth) space, and include extrapolated near offsets.

2. The output dataset is defined by shot (**s**) and receiver (**r**) locations, and is independent of the input dataset.

3. Each trace in the input dataset also has a subsurface line (SSL) number (L) and unique trace number (T) that can be used to identify the trace within the dataset. The input dataset is assumed to be split into SSLs. This idea can be generalized to any subdivision of the input dataset, but the SSL based subdivision will be used in the descriptions in this document as it is the most common.

4. A differential moveout correction can be used to map traces from one offset to another (Levin, 2002).

Algorithm

The algorithm consists of three steps.

1. Compute indices defining which traces need convolving from each pair of SSLs, and the desired offsets of these traces. This step requires only header data.

2. For every pair of SSLs, apply differential moveout correction to simulate data at the desired offsets, and perform the convolutions defined by step 1. Stack the convolutions for each output trace. This step only requires reading data for two SSLs, and is analogous to stacking the multiple contribution gathers (MCGs) in the inline direction for the 3D SMP process.

3. Stack the partially stacked convolutions for each output trace from all the pairs of SSLs. This is analogous to stacking crossline MCGs for the 3D SMP process.

[0027] More details of each step are given in the following sections.

Step 1

For each output trace (**s**, **r**) with associated indexes (L_o, T_o):

Define the aperture (area of potential downward reflection points (DRPs)) based on **s** & **r**, as shown in the figure.

Grid the aperture into discrete DRPs. The grid spacing is arbitrary but will have cost and aliasing implications.

For each DRP, **x**:

Compute desired shot-side midpoint ($\mathbf{m}_S$), offset (x_S) and azimuth (θ_S) based on (**s**, **x**), as shown in the figure.

Compute desired receiver-side midpoint ($\mathbf{m}_R$), offset (x_R) and azimuth (θ_R) based on (**x**, **r**), as shown in the figure.

Determine the closest input trace to ($\mathbf{m}_S$, x_S, θ_S) by minimizing an objective function (see below). Record the trace indices (L_S, T_S) and the target offset x_S.

Determine the closest input trace to ($\mathbf{m}_R$, x_R, θ_R) by minimizing an objective function (see below). Record the trace indices (L_R, T_R) and the target offset x_R.

Write (L_o, T_o, L_S, T_S, x_S, L_R, T_R, x_R) to a convolution index file (CIF).

End.

End.

Split the CIF into separate files for each pair of input SSLs (L_S, L_R). If $L_S>L_R$ then swap the roles of S and R such that $L_S \leq L_R$. Sort the file on Lo, To, and Ts. Denote the resultant file CIF(L_S, L_R).

Step 2

For each CIF(L_S, L_R):

For each output trace (L_o, T_o):

Initialize a partial stack trace, S(L_o, T_o; L_S, L_R)

For each trace pair (T_S, T_R):

Extract the input traces defined by T_S and T_R.

Apply differential moveout to the desired offsets x_S and x_R.

Convolve the resultant traces.

Add the convolution to the partial stack trace S.

End.

Write the partial stack trace to disk.

End.

End.

Step 3

Stack the partial stack traces S(L_o, T_o; L_S, L_R) over L_S and L_R for each output trace defined by (L_o, T_o) to get the predicted multiples. Apply a 3-D rho-filter in order to correct for the stacking effect on the wavelet, and deconvolved the source signature as is standard practice in 2D and 3D SRME.

__Objective function__

The objective function defines the closeness of two traces, based on their midpoints, offsets and azimuths. An example is

$$D^2 = |\mathbf{\Delta m}|^2 + w_x\,|\mathbf{\Delta}x|^2 + w_\theta\,|\mathbf{\Delta}\theta|^2$$

where D is the "distance" between the traces, $\mathbf{\Delta m}$, $\mathbf{\Delta}x$ and $\mathbf{\Delta}\theta$ are the differences in midpoint, offset and azimuth respectively, and w_x and w_θ are weights defining the relative importances of errors in offset and azimuth to errors in midpoint. Note that w_x is dimensionless, whereas w_θ has dimensions of, for example, $(m/^o)^2$. It is expected that w_θ will often be zero due to poor azimuth coverage of the input dataset. Since differential moveout correction provides at least partial compensation for offset errors, it might be expected that these are less important than errors in the

midpoint, for which there is no correction. There should also be a minimum value for the minimized objective function, above which the differential moveout correction is considered inadequate and there is deemed to be no matching trace. This will leave a hole in the MCG but should only occur near the edge of the survey.

The idea of selecting a nearest trace from the input dataset as a substitute for a desired trace was suggested by Sun (1999). The above description extends this idea to totally irregular data, and adds flexibility.

Cost

[0028] The basic computational (CPU) cost per output trace is equivalent to that for 3D SMP, assuming the aperture and the sampling of the MCGs are the same. This is true because the number of convolutions is the same. There will be some extra cost associated with building the CIF, but this is expected to be small compared to the cost of the convolutions. If the convolutions are computed in the frequency domain (as is normal), then the Fourier transforms need only be done once per input trace, and the inverse transforms once per output trace.

[0029] The data I/O may be more expensive than for 3D SMP, since data from two SSLs are required at once. The extra elapsed time associated with this is very dependent on disk access and network speeds.

[0030] Figure 5 illustrates a computer network 500, into which embodiments of the invention may be implemented. The computer network 500 includes a system computer 530, which may be implemented as any conventional personal computer or workstation, such as a UNIX-based workstation. The system computer 530 is in communication with disk storage devices 529, 531, and 533, which may be external hard disk storage devices. It is contemplated that disk storage devices 529, 531, and 533 are conventional hard disk drives, and as such, will be implemented by way of a local area network or by remote access. Of course, while disk storage devices 529, 531, and 533 are illustrated as separate devices, a single disk storage device may be used to store any and all of the program instructions, measurement data, and results as desired.

[0031] In one embodiment, seismic data from geophones are stored in disk storage device 531. The system computer 530 may retrieve the appropriate data from the disk storage device 531 to perform the 3-D surface multiple prediction according to program instructions that correspond to the methods described herein. The program instructions may be written in a computer programming language, such as C++, Java and the like. The program instructions may be stored in a computer-readable memory, such as program disk storage device 533. Of course, the memory medium storing the program instructions may be of any conventional type used for the storage of computer programs, including hard disk drives, floppy disks, CD-ROMs and other optical media, magnetic tape, and the like.

[0032] According to the preferred embodiment of the invention, the system computer 530 presents output primarily onto graphics display 527, or alternatively via printer 528. The system computer 530 may store the results of the methods described above on disk storage 529, for later use and further analysis. The keyboard 526 and the pointing device (e.g., a mouse, trackball, or the like) 525 may be provided with the system computer 530 to enable interactive operation.

[0033] The system computer 530 may be located at a data center remote from the survey region. The system computer 530 is in communication with geophones (either directly or via a recording unit, not shown), to receive signals indicative of the reflected seismic energy. These signals, after conventional formatting and other initial processing, are stored by the system computer 530 as digital data in the disk storage 531 for subsequent retrieval and processing in the manner described above. While Figure 5 illustrates the disk storage 531 as directly connected to the system computer 530, it is also contemplated that the disk storage device 531 may be accessible through a local area network or by remote access. Furthermore, while disk storage devices 529, 531 are illustrated as separate devices for storing input seismic data and analysis results, the disk storage devices 529, 531 may be implemented within a single disk drive (either together with or separately from program disk storage device 533), or in any other conventional manner as will be fully understood by one of skill in the art having reference to this specification.

[0034] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

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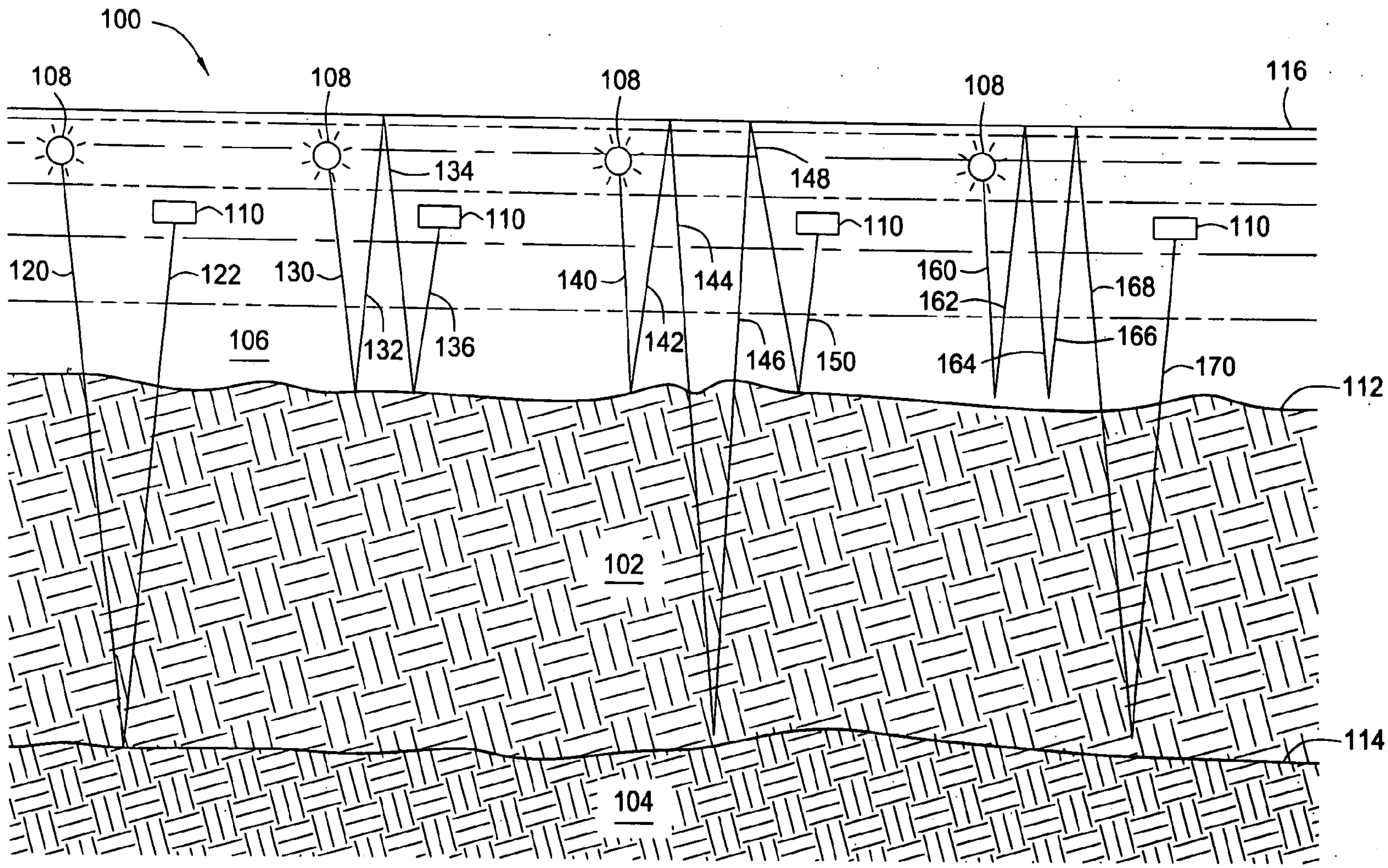

FIG. 1
(PRIOR ART)

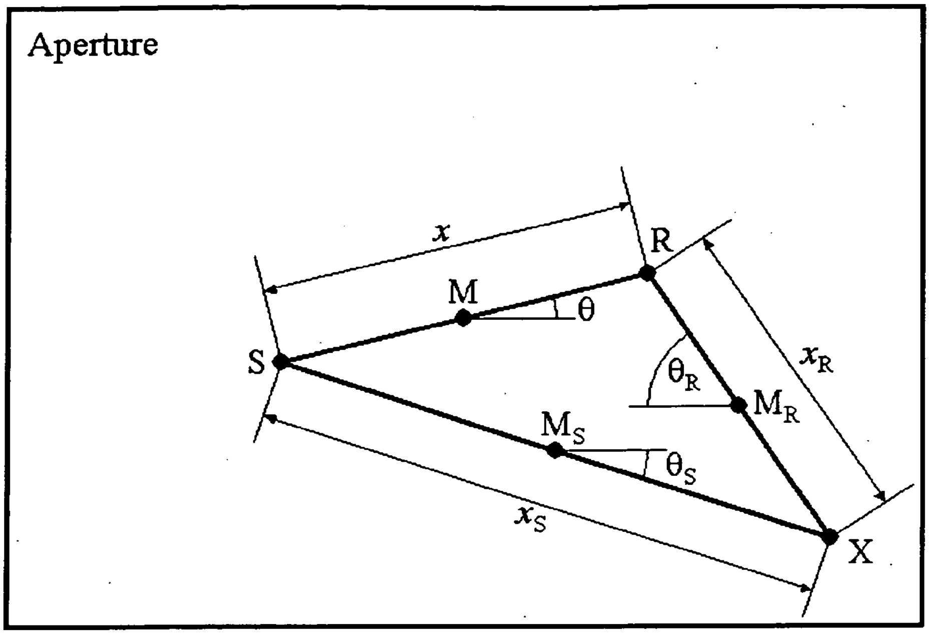

Figure 2: **Plan view of the geometry.**

2 datasets

1. TARGET. Header dataset defining locations for predicted multiples
2. INPUT. Recorded data (no regularisation, but extrapolated to zero offset) partitioned into subsets, typically sub-surface lines (SSLs)

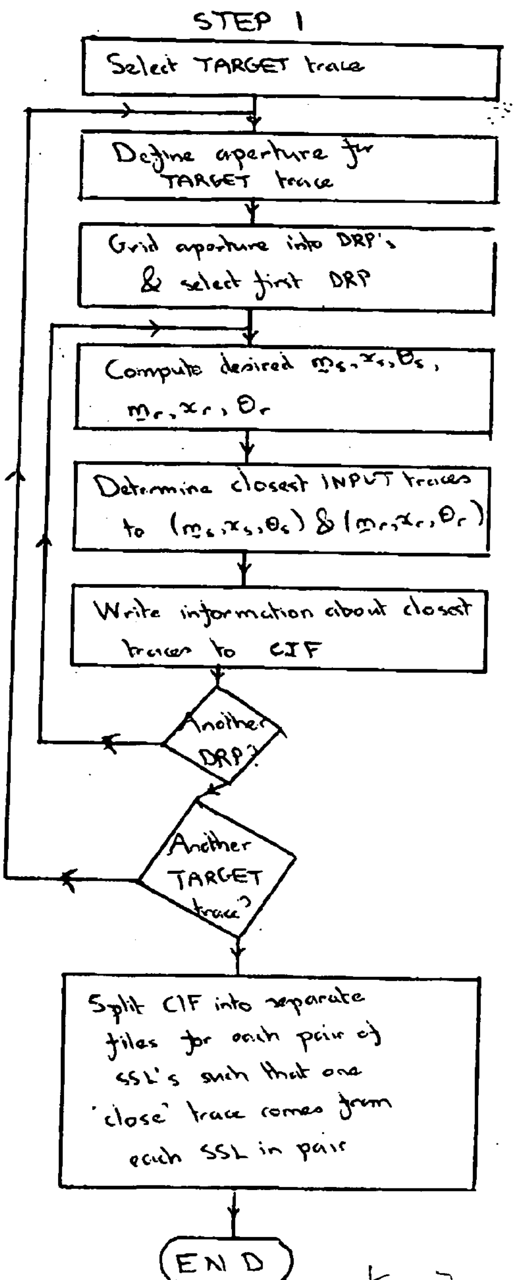

Fig. 3

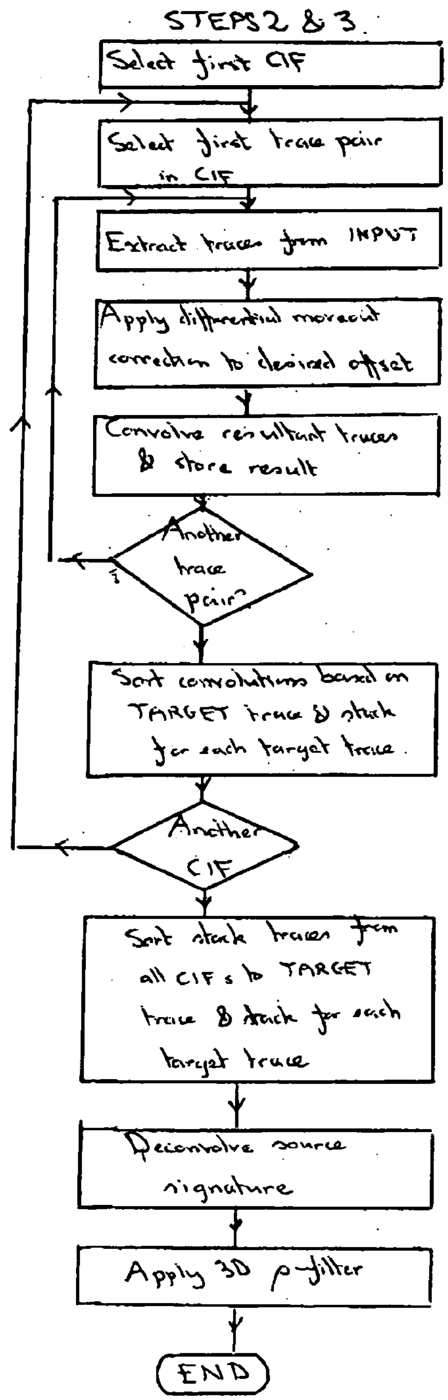

Fig. 4

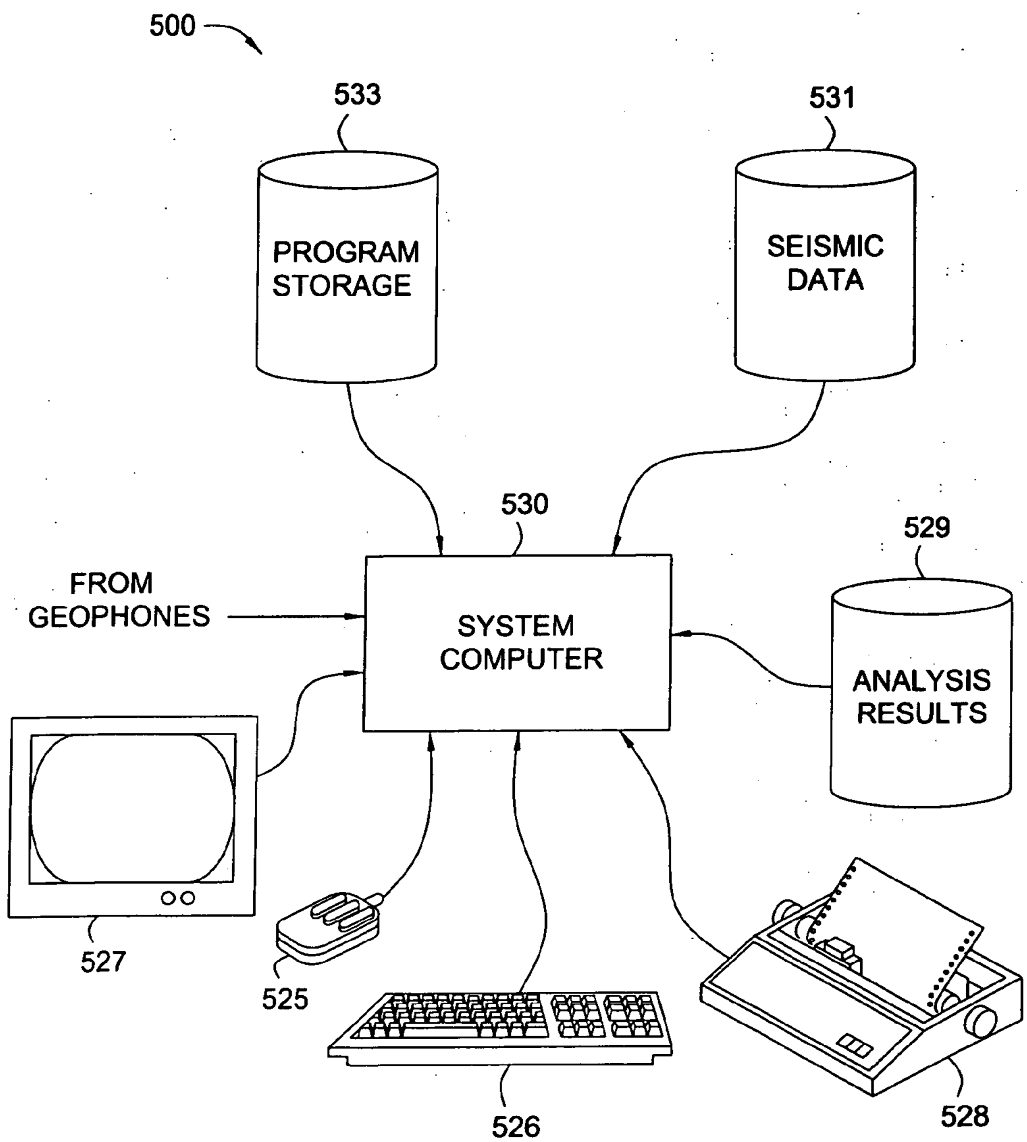
500
533
PROGRAM STORAGE
531
SEISMIC DATA
530
SYSTEM COMPUTER
FROM GEOPHONES
529
ANALYSIS RESULTS
527
525
526
528

FIG. 5